Traverse Planning for Mars Surface Exploration

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Overview

Background: Goals, traverse planning needs
Heuristic for direction of travel
Heuristic for minimum cost traverse
High-level process for traverse planning
Traverse Examples

- Apollo 14 EVA2
- Rover deploys communication and sensing network

Conclusions

Goals of Traverse Planning

Maximum Science Return

For long duration operations, must consider:

- Value/Cost Criteria
- Effect of actions on sustainable operations
- Risk/Uncertainty

Traverse Planning Needs

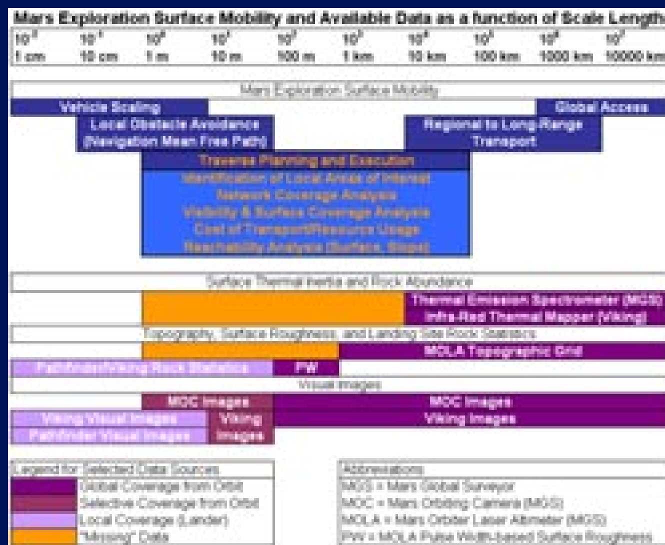
Plan appropriate traverse

- Maximize science return / minimize cost
- Minimize cost if over-riding goal is to get from point A to point B
  - Predict cost of mobility
  - Predict energy expenditures or other resource usage

Validate traverse

- Compatible with operational constraints, static and dynamic (e.g., average energy expenditure, peak energy expenditure)
- Compatible with general "flight rules"

Mobility and Access for Mars



Mars is a data-rich environment for surface exploration, but additional data would be useful for traverse planning and execution.

Heuristic for Local Direction of Travel

Height-Height Correlation Function

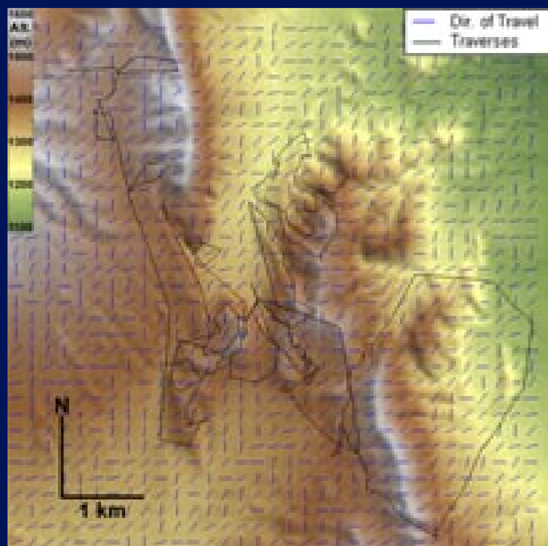
$C(\mathbf{r})=\langle|h(\mathbf{x}+\mathbf{r})-h(\mathbf{x})|^2\rangle_x^{1/2}$

Represents directional dependence of topographic power at a given scale length (r)

Min(C(**r**)) provides a heuristic for direction of travel for travel over a given scale length.

Can compute C(**r**) based on digital elevation model for desirable scale lengths

Heuristic for Local Direction of Travel



Example: Field geology traverses in the Bird Spring Mountains, Nevada, plotted with Local Direction of Travel heuristic indicators (r~300m).

Heuristic for Minimum Cost Traverse

Define starting and ending points A and B

Randomly choose N points near or between A and B

Build a graph of possible traverse routes

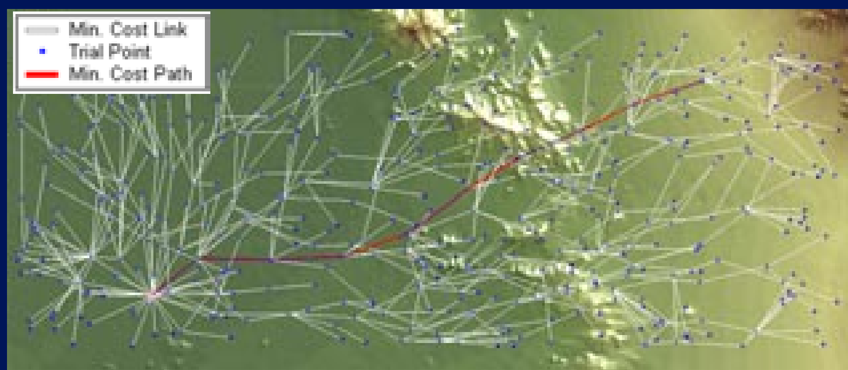
- Create an edge between each set of nearby points x and y
- Assign each edge a cost by applying some cost model to a path between x and y
  - Use some heuristic to choose the direction of traversal

Apply Dijkstra's shortest (minimum cost) path algorithm to yield a spanning tree T centered at A

Extract the path from A to B from tree T

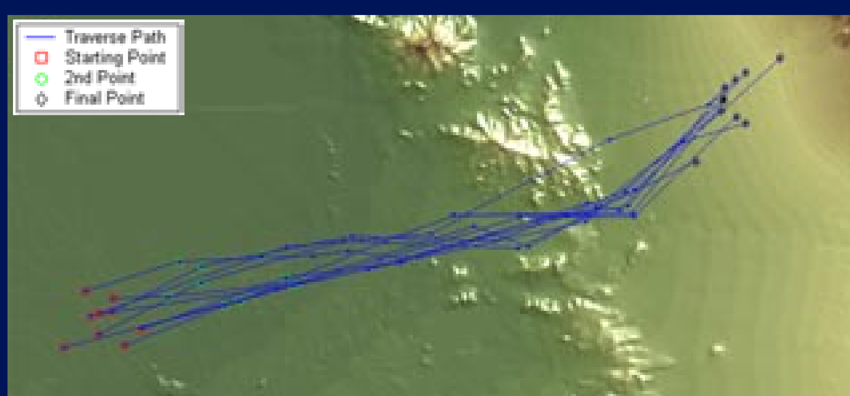
Minimum Cost Traverse Example

The heuristic does not always yield optimal results!



Minimum Cost Traverse Example (2)

Over many trials, generally yields good results.



Process for Traverse Planning

A simple framework for traverse planning

- Evaluate Path Independent Surface Conditions and Accessibility (slope, surface type, restricted areas)
- Identify Sites and Activities of Interest (sampling, equipment deployment/setup)
- Identify initial possible traverse(s)
- Evaluate Path Dependent Surface Conditions and Accessibility (surface visibility, sun angles, shadowing, slopes, heat balance)
- Perform Flight Rule Validation
- Modify or Accept the Traverse Plan
- Communicate the Traverse Plan (enable coordination)

Traverse Example: Apollo 14 EVA2

Path Independent Considerations

- Slope restriction of [0 15] degrees

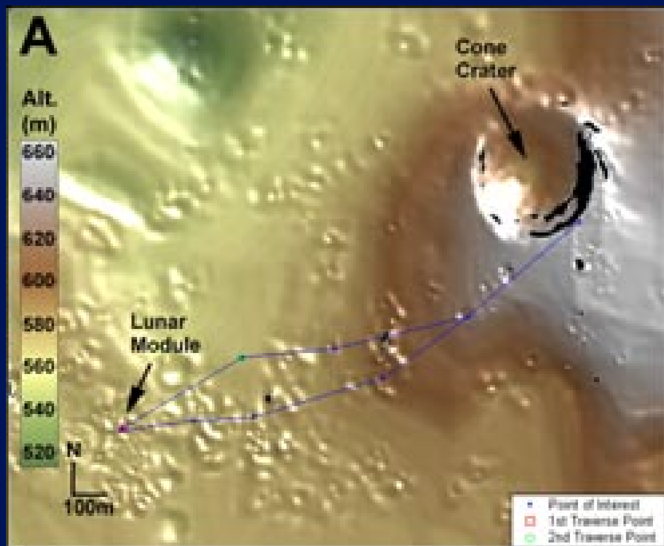
Sites and Activities of Interest

- Geological stations identified from photographs

Identify initial possible traverse(s)

- Traverse order natural due to “out-and-back” traverse structure
- Uphill first-half, downhill second half for contingencies

Traverse Example: Apollo 14 EVA2



Planned traverse and [0 15] slope restriction

Traverse Example: Apollo 14 EVA2

Actual traverse and [0 15] slope restriction

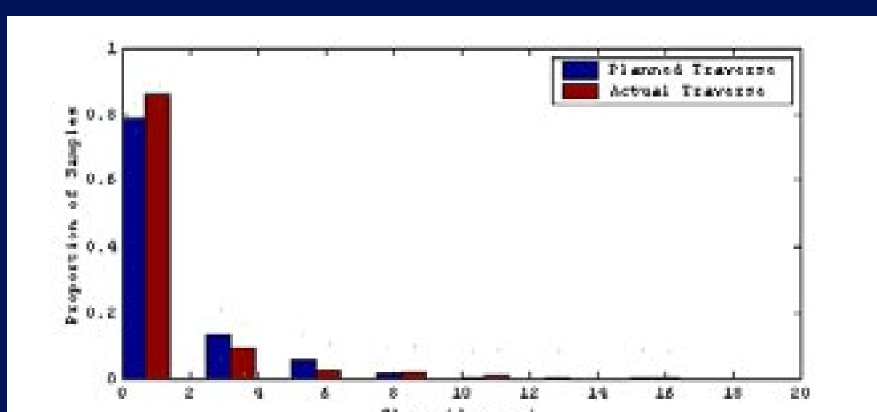
Traverse Example: Apollo 14 EVA2

Path Dependent Considerations

- Metabolic Cost
  - Load carrying model (Santee et al.) = 1318 kJ
  - Actual ~ 1550 kJ
  - Based only on traverses between geologic stations
  - No modeling of any other exploration activities
  - No modeling of Mobile Equipment Transporter
- Slopes
- Surface Visibility

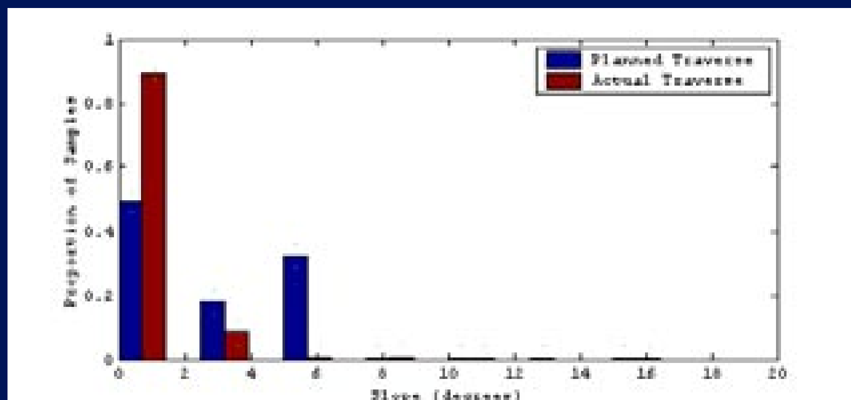
Traverse Example: Apollo 14 EVA2

Slopes: spatial sampling along traverse



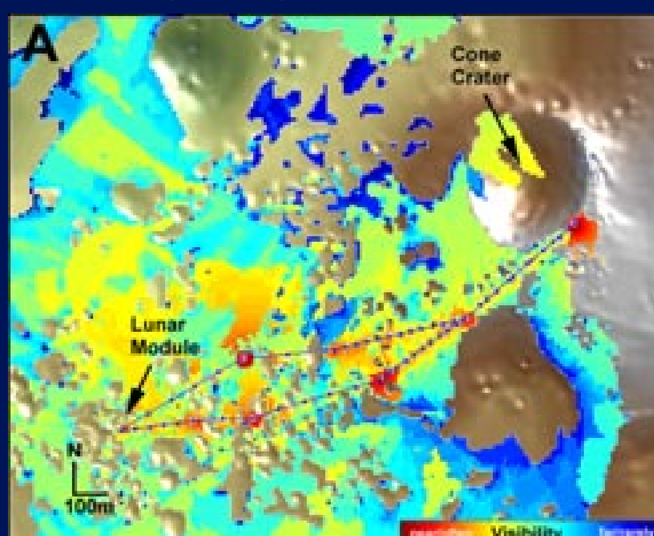
Traverse Example: Apollo 14 EVA2

Slopes: temporal sampling along traverse



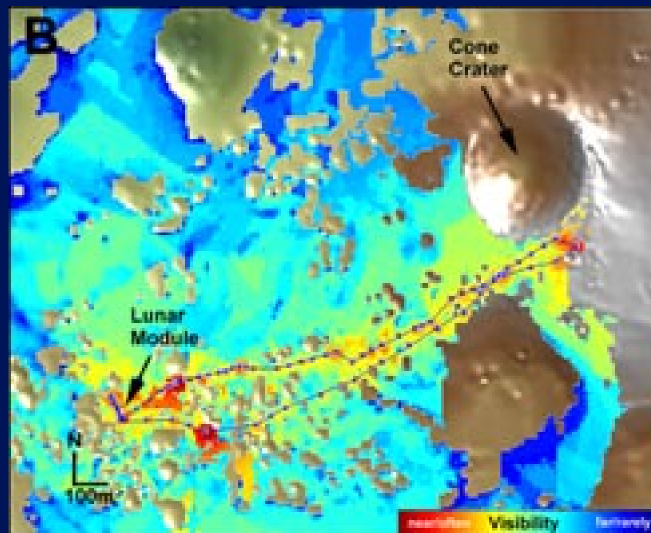
Traverse Example: Apollo 14 EVA2

Surface
Visibility
Of
Planned
Traverse



Traverse Example: Apollo 14 EVA2

Surface Visibility Of Planned Traverse

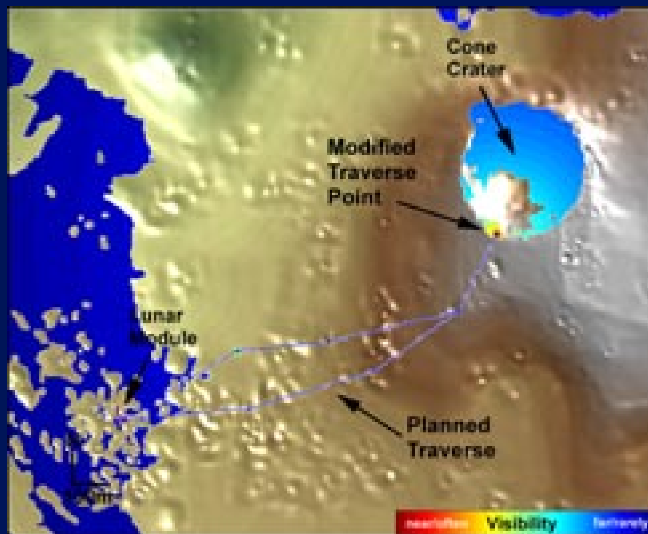


Traverse Example: Apollo 14 EVA2

- Flight Rule Validation
  - Performed by Mission Control and “Back Room” planners in real-time
- Example modification of the traverse plan: change Cone Crater geological station location to south-west rim
  - Shorter total traverse distance
  - Enhanced surface visibility during traverse
  - Excellent view into Cone Crater and of Lunar Module
  - Better sun-relative traverse direction (cross-sun)
- Communicate the Traverse Plan
  - Voice communications – real-time adjustments

Traverse Example: Apollo 14 EVA2

Visibility at modified Cone Crater location



Traverse Example: Rover Traverse

Goal: Traverse from home base to remote site while deploying sensor probe / communication relay network linking the two sites.

(Crater Lake used as analog terrain.)

Traverse Example: Rover Traverse

Slopes limited to [0 20] degrees.

Nominal traverse velocity 0.5 m/s.

Effective antenna height 1.5 m (rover and sensor/communication wands).

Nominal communication range of 1 km.

Rover energy expenditure model

- 50 kg rover
- Flat surface: 0.216 Ws/m/kg + 5 W baseline
- Slopes: 0.0263 Ws/m/kg/deg; 30% energy recovery on downhill slopes
- Model based on Lunar Roving Vehicle

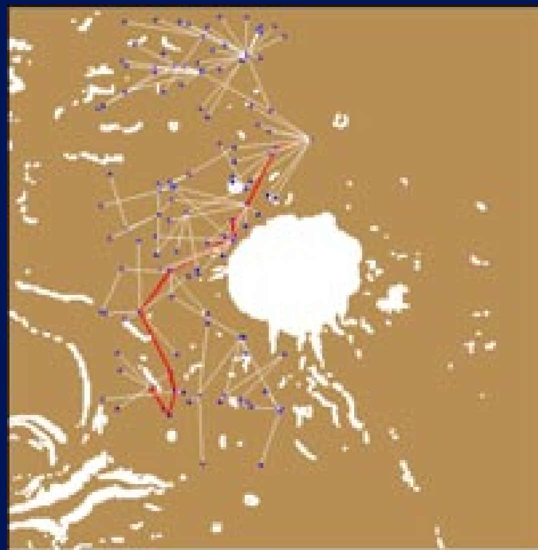
Traverse Example: Rover Traverse

Strategy for traverse planning and execution

```
do while and(not(mission accomplished), not(give up))
   compute visible region of surface
   compute minimum cost traverse to destination
   if minimum cost traverse contains a visible location
      traverse to visible location
      deploy a data wand
      if and(previous wand visible, target visible)
         mission accomplished
      else if previous wand not visible
         give up
loop
```

Traverse Example: Rover Traverse

Example
Minimum
Cost
Traverse



Traverse Example: Rover Traverse

```
INITIALIZING ROVER SIMULATION

ROVER STATE: id=1 x=558671 y=4743633 z=1874 kJ=0 t=0
NETWORK STATE: Nodes released=0 SourceVisible=1 TargetVisible=0 NodesConnected=1
MeanCost=NaN
ROVER IDENTIFIED NEXT COMM/SENSOR NODE at X: 556985 Y: 4742685 Z: 1908
ROVER TRAVERSING FROM X: 558671 Y: 4743633 Z: 1874 to X: 556985 Y: 4742685 Z: 1908

ROVER STATE: id=2 x=556985 y=4742685 z=1908 kJ=34 t=0
NETWORK STATE: Nodes released=1 SourceVisible=1 TargetVisible=0 NodesConnected=2
MeanCost=1.25
ROVER IDENTIFIED NEXT COMM/SENSOR NODE at X: 557465 Y: 4741885 Z: 2033
ROVER TRAVERSING FROM X: 556985 Y: 4742685 Z: 1908 to X: 557465 Y: 4741885 Z: 2033

ROVER STATE: id=3 x=557465 y=4741885 z=2033 kJ=65 t=0
NETWORK STATE: Nodes released=2 SourceVisible=1 TargetVisible=0 NodesConnected=3
MeanCost=1.16
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
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ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR 1ST TRAVERSE
POINT
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, TRYING FOR TARGET
ROVER FAILED TO FIND SUITABLE NEXT COMM/SENSOR NODE LOCATION, GIVING UP
```
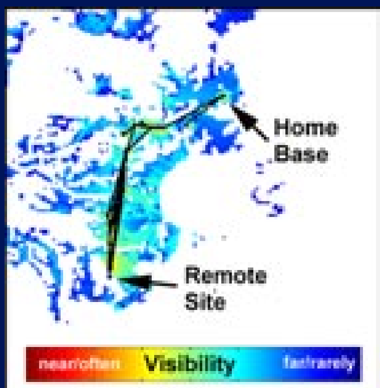

Traverse Example: Rover Traverse

An Example of a Successful Traverse



Conclusions

- Following some structured traverse planning process might have resulted in changes in the planned Apollo 14 EVA2 traverse
- Can apply traverse planning process at different levels of fidelity, or can focus on only some aspects of traverse
- Structured traverse planning process can be automated
- Can allow rapid re-planning even with complex or numerous flight rules
- Automated re-planning especially valuable when have long light-travel-time delays (reduce “wasted” time)

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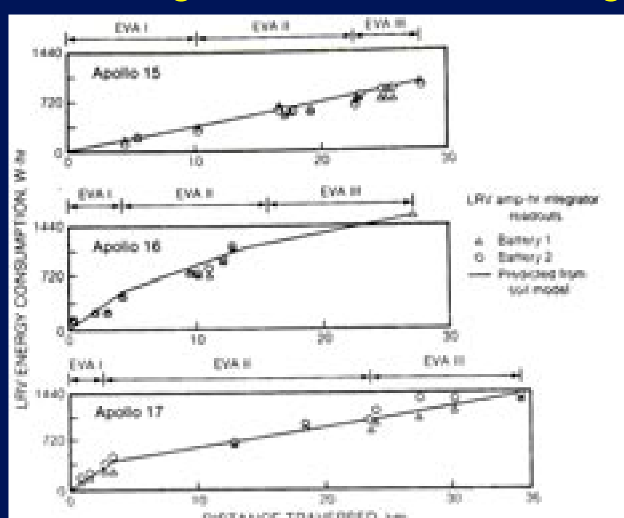
Lunar Roving Vehicle: Soil Modeling



[Heiken et al., 1991], p. 528